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ARE TROPICAL CIRRUS BRIGHTER THAN MID-LATITUDE CIRRUS?

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Recent measurements during FIRE II, in the tropics and elsewhere support an emerging hypothesis about the role of stratospheric mixing in determining the microphysical and radiative properties of cirrus clouds. This is only a working hypothesis, and may change as new measurements become available. We will begin by reviewing the conditions under which certain types of ice crystals form.

BACKGROUND

Polycrystalline ice crystals, or spatial crystal habits, often form from freezing cloud or haze droplets, with rosettes or side planes (also called crossed plate crystals) forming at T < -20°C (Hallett and Mason 1964; Magono and Aburakawa 1968). Side planes grow well at low supersaturations relative to ice (≤ 10%), while bullet or column rosettes require higher supersaturations to grow, and may dominate at higher supersaturations (Furukawa 1982; Furukawa and Kobayashi 1978). Side planes grow at lower supersaturations since their growth is driven by the surface kinetics of the ice lattice (grain boundary dislocations) in addition to the vapor gradient, while the two-dimensional growth mechanism of rosettes is only driven by the vapor gradient. In other words, the condensation coefficient (the probability of an impinging water molecule incorporating into the ice lattice) for side planes should be greater at low supersaturations than for crystals which grow by the two dimensional nucleation mechanism, such as columns, plates and rosettes.

Takahashi and Kuhara (1993) sent specially developed radiosondes into cumulonimbus clouds over Pohnpei, Micronesia. High concentrations of side plane ice crystals were reported near the tropopause, around -63°C. Flights in cirrus with the DRI replicator during TOGA COARE did not get near the tops of anvil cirrus. The replicator was mounted on an aircraft wing, with a 3 mm x 8 mm intake slot for ice crystals. The ice particles impacted the formvar coated replicator film at aircraft speeds, so that mid-to-large size ice crystals tended to be shattered. The data has yet to be quantified, although preliminary inspections indicate high concentrations of planar type ice crystals dominated. Although difficult to describe, the "best guess" at this time is that the crystals are mostly fragments of side planes.

HYPOTHESIS

Evidence of side planes dominating in anvil cirrus suggests that supersaturations with respect to ice were low. Since water vapor densities tend to be lowest in the upper troposphere relative to lower levels, little moisture is available for condensation. Modest changes in the demand for moisture by growing ice crystals, due to changes in ice crystal concentrations, could thus affect supersaturations. In the tropics, the tropopause is generally around 16 km (Rosen and Hofmann 1975), and cumulonimbus clouds often penetrate into the stratosphere up to 18 or 20 km (Ramanathan and Collins 1991). Between 16 and 20 km in the tropics, there is generally a four fold increase in the mixing ratio (number of particles per milligram of air) of aerosol particles > 0.3 μm diameter (Rosen and Hofmann 1975). These are ideal although large CCN sizes. Aerosol mixing ratios in both the middle and upper troposphere are low relative to the lower stratosphere in the tropics. Thus, relatively high CCN concentrations may be entrained into cumulonimbus tops and cirrus anvils, which may nucleate haze droplets which freeze to form ice crystals (Sassen and Dodd 1988). Nucleation rates of these polycrystals should be relatively high, and the competition for vapor should drive down the supersaturation. This could produce a rapid transition in crystal habit from rosettes to side planes (a few rosettes were observed in the replicator film from TOGA COARE).

The above scenario should produce anvil cirrus with relative high albedos for the following reasons: (1) entrainment of stratospheric CCN results in high concentrations of small ice crystals, which yields more ice surface area per unit volume of cloudy air for a given ice water content (IWC). This results in greater optical depth and albedo. (2) Side planes are very complex in structure, and appear to promote ice crystal aggregation in cirrus (Mitchell et al. 1993, these preprints). Side plane crystals and aggregates containing them are expected to produce greater side- and backscatter than other crystal types, since multiple pairs of refraction events are likely as light passes through these particles. (3) Although not quantified yet, it appears that side planes may have relatively high projected area to mass ratios. The amount of energy scattered per unit mass would then be relatively high, promoting greater cloud averaged single scatter albedos in the near IR. The near IR accounts for about 15% of the solar irradiance at cirrus levels.

As shown in Mitchell et al. (1993, these preprints), aggregation may be an important growth process in cirrus when side planes are present. Aggregation acts to reduce the surface area of the size distribution and thus reduces optical depth and cloud averaged single scatter albedo. An increase in IWC will increase the aggregation rate (Mitchell 1991), so that the relation between optical depth and IWC may not be linear. If side planes allow significant aggregation to occur in cirrus, it must be shown that the radiative effects of aggregation are secondary to the effects mentioned above which would enhance albedo.

On a final note, a somewhat bizarre observation made during TOGA COARE may have relevance here. Scientists flying through cirrus in the vicinity of -40°C observed substantial amounts of liquid water impacting the aircraft windshield. Similar observations have been made by pilots and scientist observers of aircraft icing while flying through cirrus at temperatures colder than -40°C. As discussed in Sassen (1992), such observations could be the result of liquid haze droplets which form below water saturation. They can exist at such temperatures due to their high solute concentrations which lowers their freezing point. Since these haze droplets should be less than about 4 μm in diameter, depending on CCN mass and relative humidity, it would take high concentrations of these haze droplets to produce the amounts of liquid observed on the aircraft windshield. As noted above, higher concentrations of large CCN may arise due to mixing with stratospheric air. Clearly, more information is needed to draw any conclusions, and it is hoped that aerosol and cloud particle measurements are available during these flight periods to evaluate this question further.

In general, this reasoning would suggest that tropical anvil cirrus, due to their mixing with stratospheric air, would be exhibit greater albedos than cirrus which did not encounter such mixing, such as most mid-latitude cirrus. However, injections of stratospheric air into mid-latitude cirrus can occur along the jet stream at tropospheric folds. CCN fluxes under these conditions can be particularly high if the stratosphere is affected by recent volcanic eruptions. This may have occurred during the FIRE II case study of 5-6 December 1991.

FIRE II CASE STUDY OF 5-6 DEC. 1991

As discussed in Sassen (1992), cirrus formed in association with a strong jet stream out of the subtropics on these days. A surge of volcanic aerosols from the Mount Pinatubo eruption accompanied the jet stream and was believed to mix with cloudy cirrus air through injections of stratospheric air along the jet stream. We will show how the ice crystals were complex planar shapes on that day, and tended to be highly aggregated. The complex shapes appear most similar to side planes, and appear polycrystalline. Linear depolarization ratios, obtained from the polarization diversity lidar, give an indication of how complex the ice particle shapes are, with higher ratios for greater complexity. The periods of greatest lidar backscatter and linear depolarization ratio corresponded to periods of high ice particle concentration when side plane habits were most dominate. Lower depolarization ratios were obtained during periods where columns were abundant in side plane/column aggregates.

More analysis needs to be done to achieve a more comprehensive understanding of the microphysics and associated radiative properties on these days before any firm conclusions can be drawn. However, the observations for this period are consistent with the hypothesis stated above. High aerosol particle concentrations from the stratosphere coincided with relatively high concentrations of planar polycrystals, which are expected to dominate under such conditions. Side planes and aggregates thereof tended to exhibit greater backscatter, owing to relatively high concentrations and complex shapes.

CLIMATE IMPLICATIONS

In the western Pacific, deep convection produces cumulonimbus-cirrus anvil cloud systems which can grow up to 10^6 km^2 in a day or less, with cirrus sometimes several hundreds of km away from their convective source (Houze and Betts 1981). Due to their spatial extent, the radiative properties of these systems are dominated by the anvils and stratiform cirrus. The albedo of these cloud systems can be as high as 60%-80% (Harrison et al. 1991). These cloud systems have been proposed by Ramanathan and Collins (1991) to act as a thermostat in regulating sea surface temperatures in the tropics, as well as enhancing the Hadley and Walker circulations. Key to understanding this phenomena is to understand why the albedo from these cloud systems is so high. The hypothesis presented here is one possible explanation for the observed high albedo of tropical cirrus. This hypothesis also implies that the albedo of tropical cirrus may be influenced by volcanic eruptions which penetrate into the stratosphere.

Major volcanic eruptions have been estimated to reduce global surface temperatures by about $1^{\circ}C$ or less (Ardanuy and Kyle 1986). The possibility that increased aerosol loading of the stratosphere may increase albedo in tropical and some mid-latitude cirrus suggests another mechanism by which volcanoes can affect climate.

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